Resettable Landing Gear for Mars Hopper

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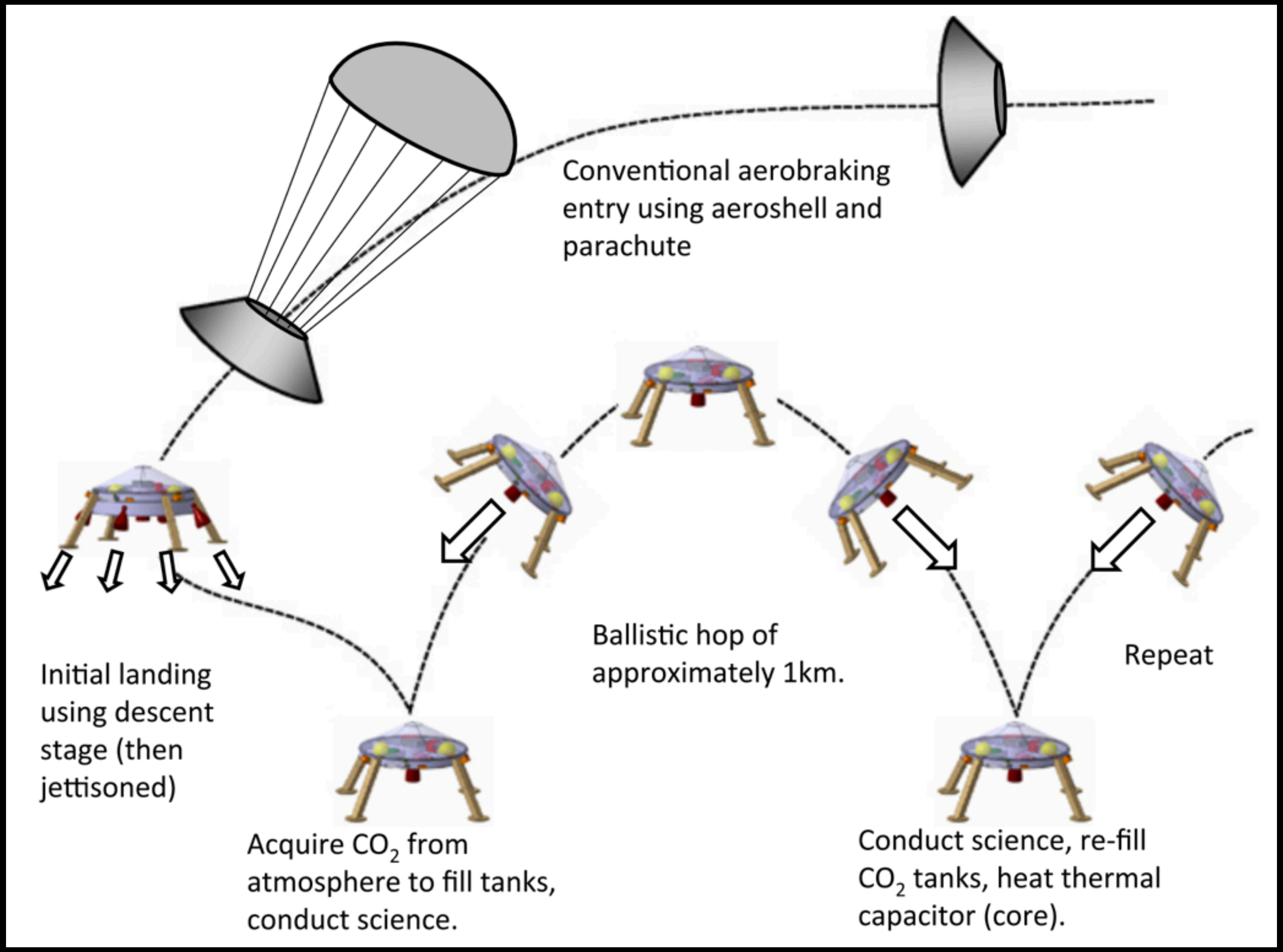
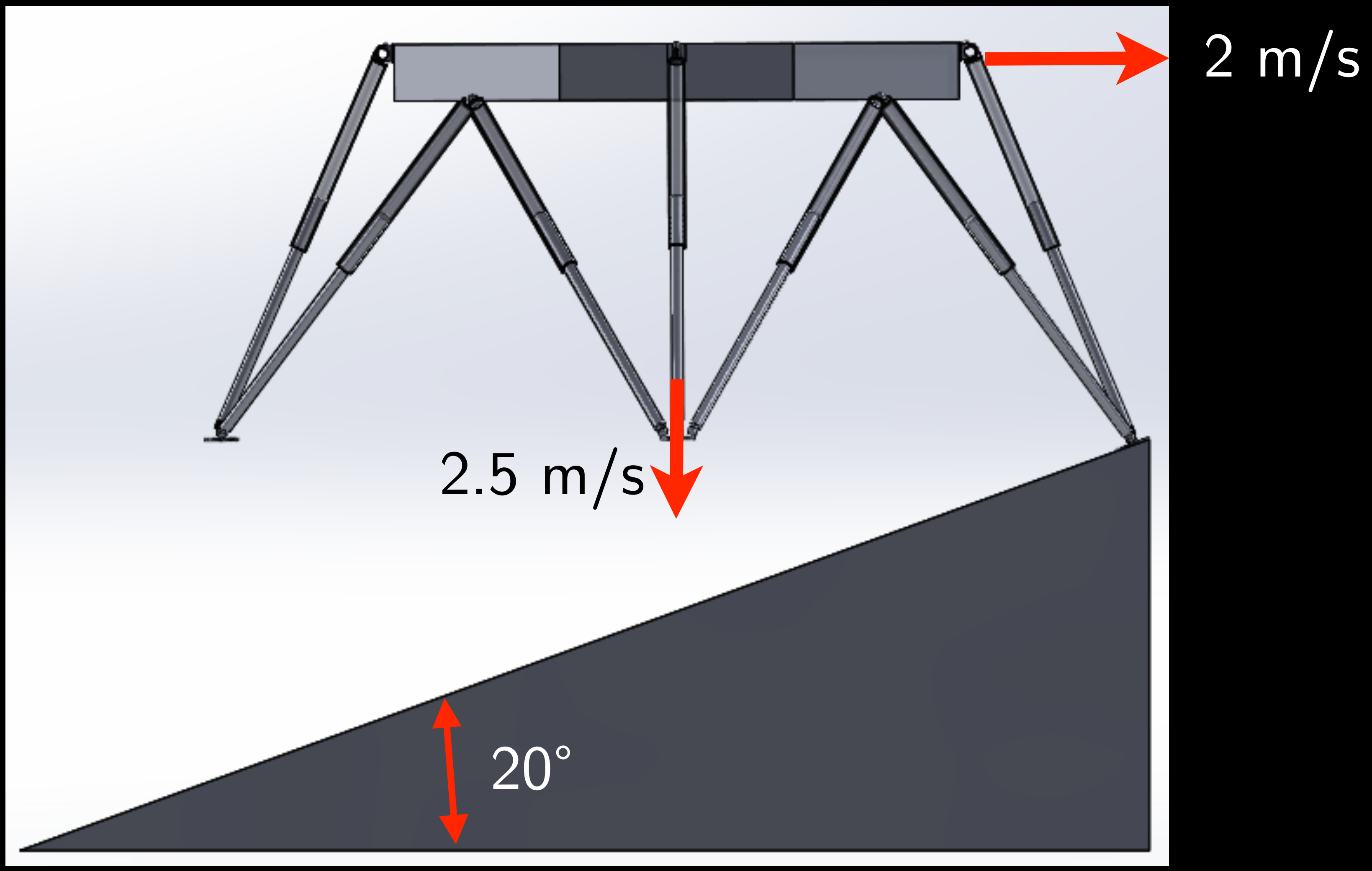
Mars Hopper

- University of Leicester Space Research Centre
- Extends mission range and capability of Mars missions
- Issue - No design for multi-use landing legs exists



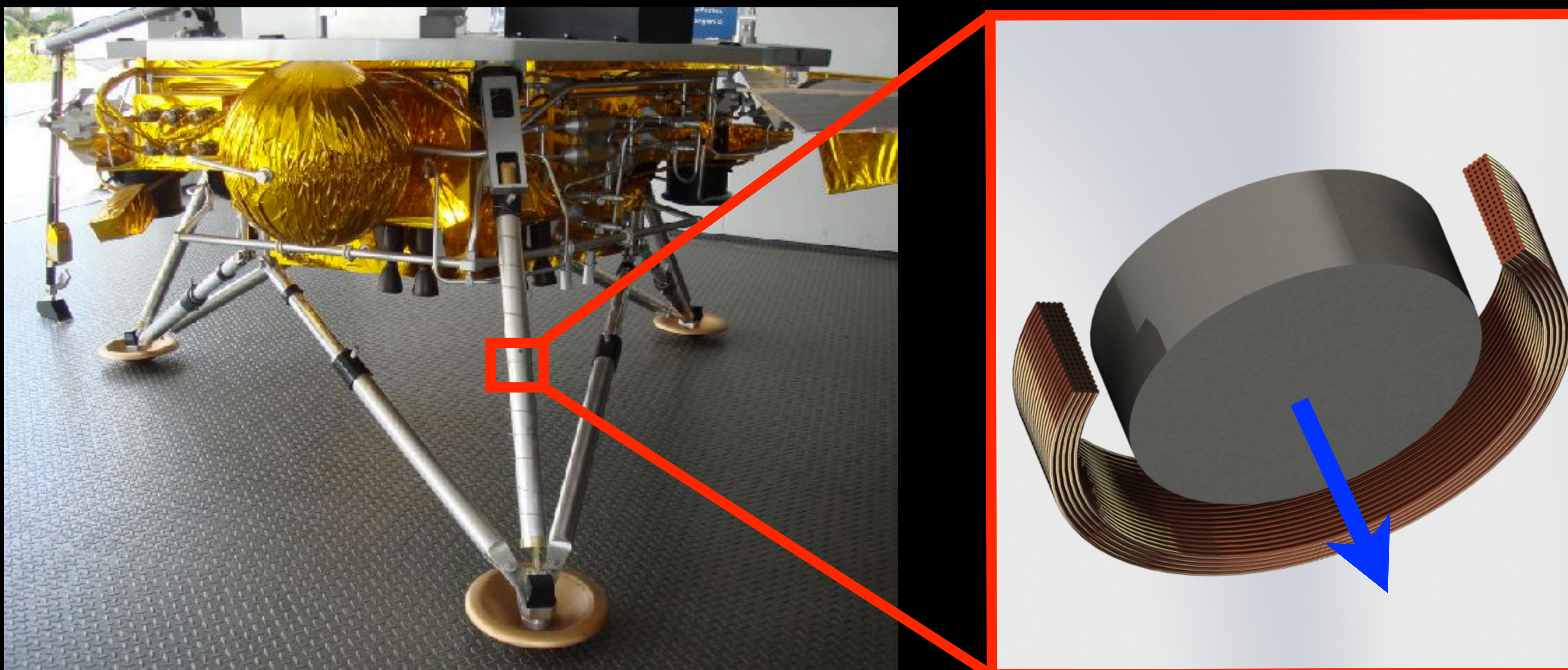
Mission Requirements



- Vehicle mass of 1000 kg
- Max 2.5 m/s vertical velocity
- Max 2 m/s horizontal velocity
- Max slope of 20°
- Max tilt angle of 2°
- Max obstacle diameter of 0.5 m

Design Concept

Electromagnetic shock absorption solution

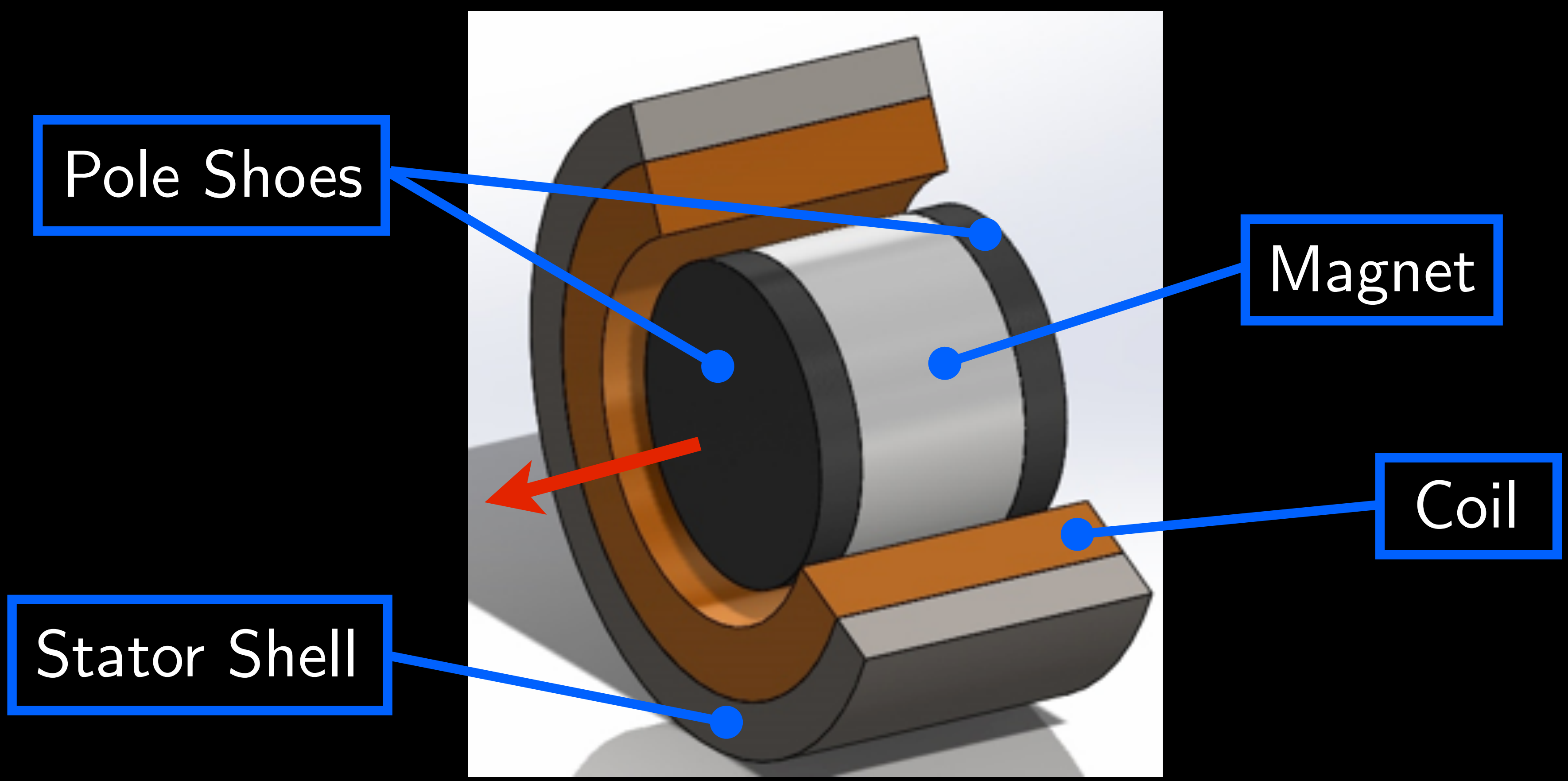


Electromagnetic Damper > Approach

- Model the shock as an ideal mechanical damper:

$$F_d = -c_d v$$

- Mover: 1 magnet capped by 2 pole shoes
- Stator: Ferromagnetic shell and single phase coil



Electromagnetic Damper > Model

- Machine constant, Kt, determined by:
  - Magnet radius
  - Magnet strength
  - Physical properties of damper

$$K_t = \frac{\pi N_a B_m r_m^2}{l_f}$$

- Resistance, R, determined by:
  - Wire radius
  - Number of turns

$$R = \frac{r_i + r_s}{r_w^2 \sigma}$$

$$L_{coil}\frac{dF_d}{dt} + R_{coil}F_d = K_t^2 v$$

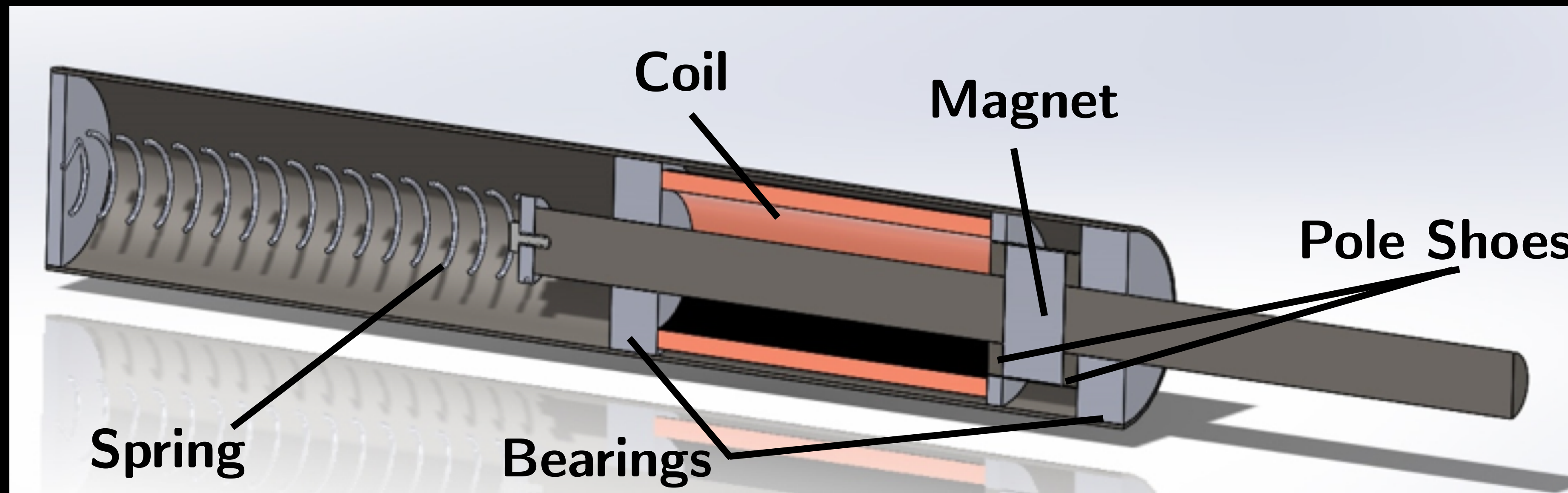
$$\tau\frac{dv}{dt} + v = F(t)$$

$$F_d = \frac{K_t^2}{R_{coil}} v$$

$$F_d = -c_d v$$

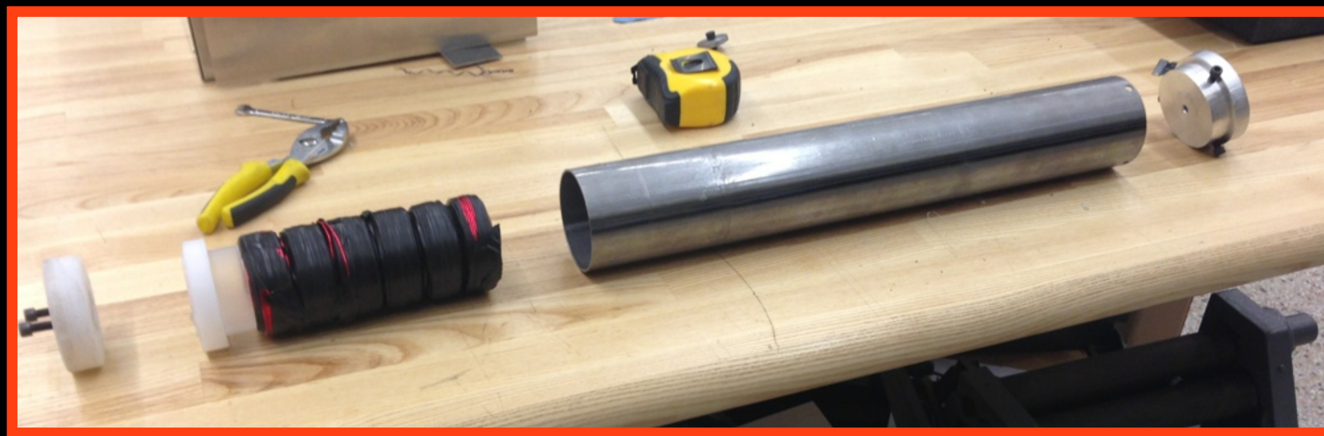
$$c_d = \frac{K_t^2}{R_{coil}}$$

Prototype Design



<table>
<tr><th>Parameter</th><th>Model Value</th><th>Determines</th><th>Determines</th><th>Determines</th></tr>
<tr><td rowspan="2">Stroke/coil length</td><td rowspan="2">0.19 m</td><td>Travel distance (+)</td><td>→</td><td>Velocity at impact (-)</td></tr>
<tr><td>Resistance (+)</td><td rowspan="3">Damping constant (-)</td><td rowspan="8">Deceleration (+)
Maximum load (+)
Velocity at impact (-)</td></tr>
<tr><td>Wire diameter</td><td>0.00145 m</td><td>Resistance (-)</td></tr>
<tr><td>Number of coil layers</td><td>5</td><td>Resistance (+)</td></tr>
<tr><td>Magnet width</td><td>0.0254 m</td><td rowspan="3">Machine constant (+)</td><td rowspan="5">Damping constant (+)</td></tr>
<tr><td>Magnet radius</td><td>0.0254 m</td></tr>
<tr><td>Number of magnets</td><td>1</td></tr>
<tr><td>Air gap width</td><td>0.0011 m</td><td rowspan="2">Machine constant (-)</td></tr>
<tr><td>Pole shoe width</td><td>0.0125 m</td></tr>
<tr><td>Spring constant</td><td>145.355 N/m</td><td colspan="2">→</td><td>Deceleration (-)
Maximum load (-)
Velocity at impact (+)</td></tr>
</table>

Prototype Construction



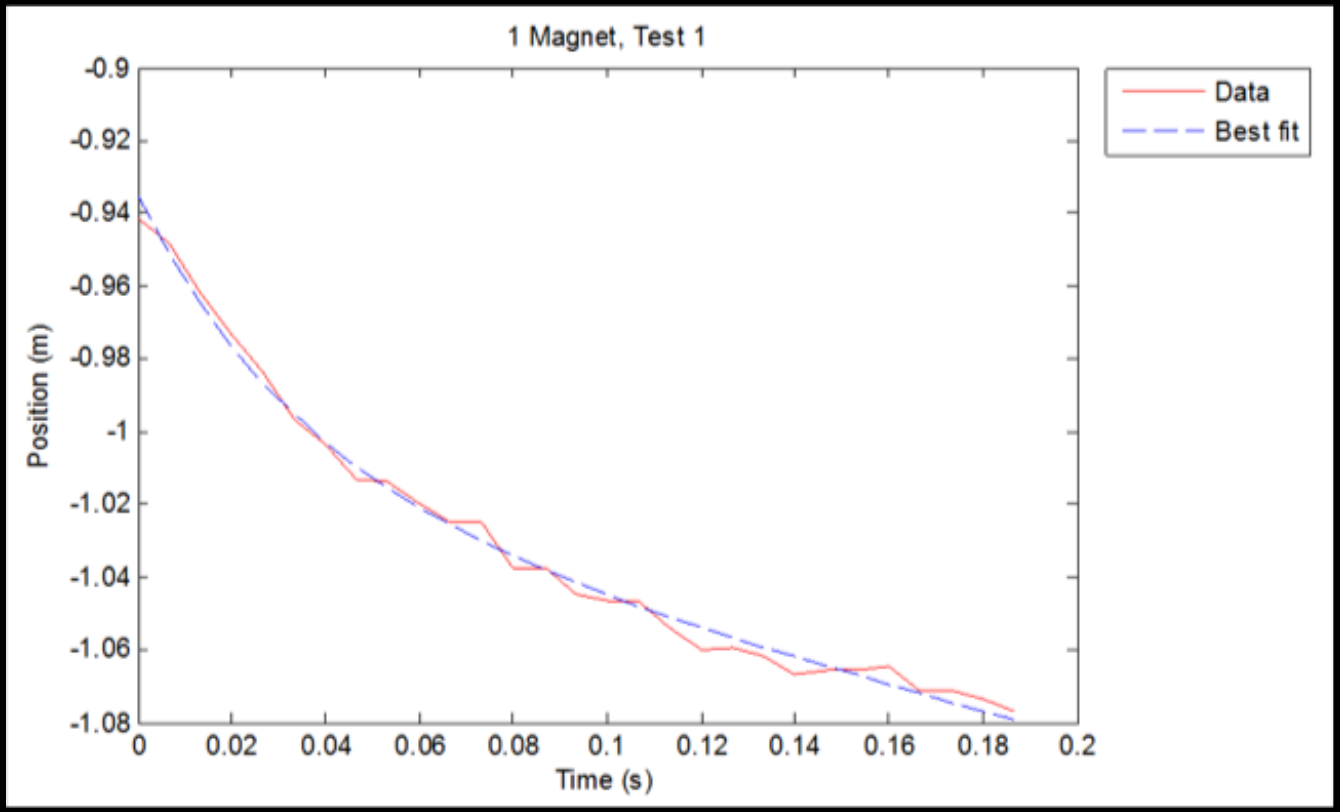
Differences from design:

- Replaced single long coil with an array of smaller coils
- Moved separator tube from mover to stator

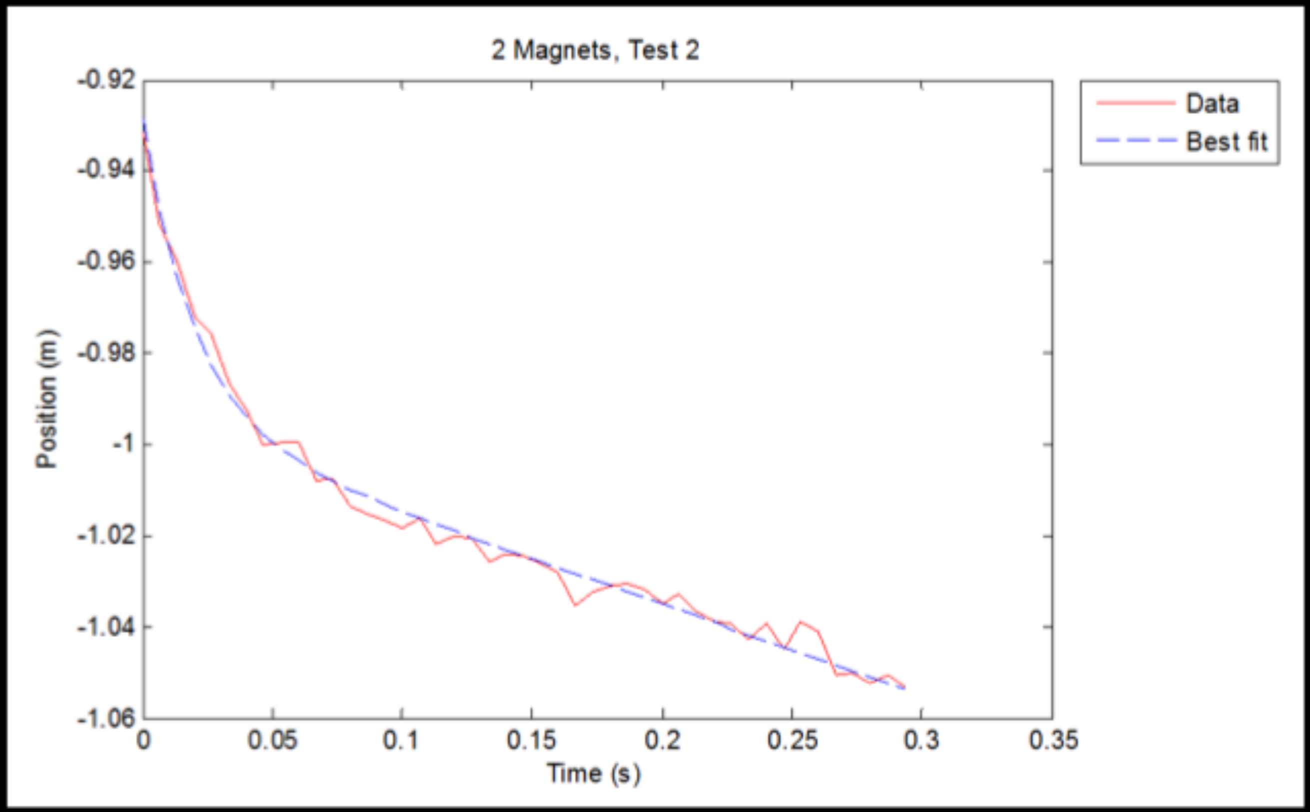
Prototype Testing

Drop tests were performed and data was gathered using an optical sensor. An equation of motion was derived and fit to the data to find the damping constant c

$$z(t) = -\frac{gm}{c}t + \frac{k_1 m}{c}e^{-\frac{c}{m}t} + k_2$$



1-Magnet configuration:
c = 91.1 ± 8.8 kg/s

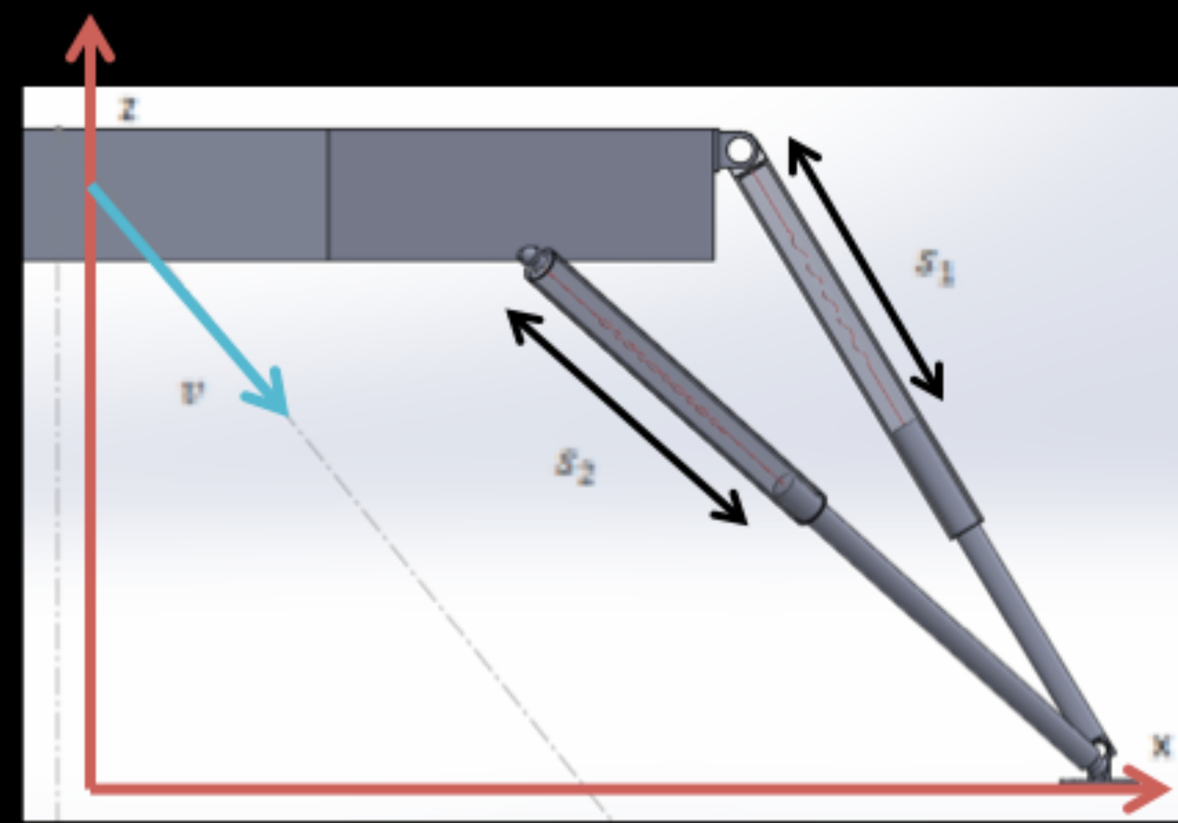


2-Magnet configuration:
c = 176 ± 14 kg/s

Touchdown Dynamics > Theory > Approach

Mathematical Model

- Generalized coordinates x and z
- 4 legs, 3 struts per leg
- Primary strut has stroke s_1, spring constant k_1 and damping constant c_1
- Secondary struts s_2, k_2, c_2



Assumptions

- Point mass $\boldsymbol{m}$ at vehicle center of gravity
- Each strut idealized as linear spring and linear dashpot
- secondary struts identical and symmetric

Touchdown Dynamics > Theory > Model

Kinetic Energy

$$T^* = \frac{1}{2} m v^2$$

Potential Energy

$$V = mgz + \frac{1}{2} k_1 s_1^2 + k_2 s_2^2$$

Generalized Work

$$dW = \Xi_1 dx + \Xi_2 dz = -c_1 \dot{s}_1 ds_1 - 2c_2 \dot{s}_2 ds_2$$

Energy dissipated by the dampers

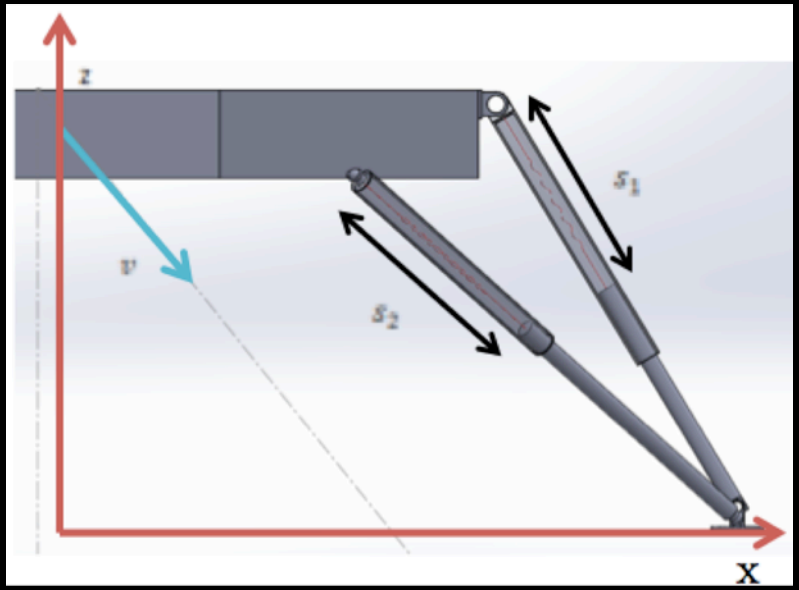
Solve for

Generalized Forces

$$\Xi_1 \text{ and } \Xi_2$$

Lagrangian

$$\mathscr{L} = T^* - V$$



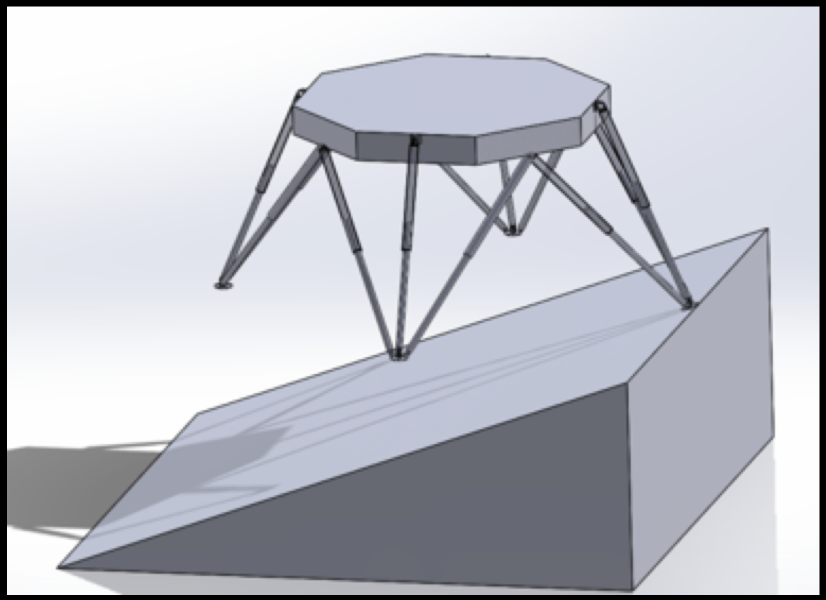
$$\frac{d}{dt}\left(\frac{d\mathscr{L}}{d\dot{x}} + \frac{d\mathscr{L}}{d\dot{z}}\right) - \frac{d\mathscr{L}}{dx} - \frac{d\mathscr{L}}{dz} = \Xi_1 + \Xi_2$$

Express $\mathcal{L}$, Ξ_1, and Ξ_2 in terms of x and z to obtain equation of motion.

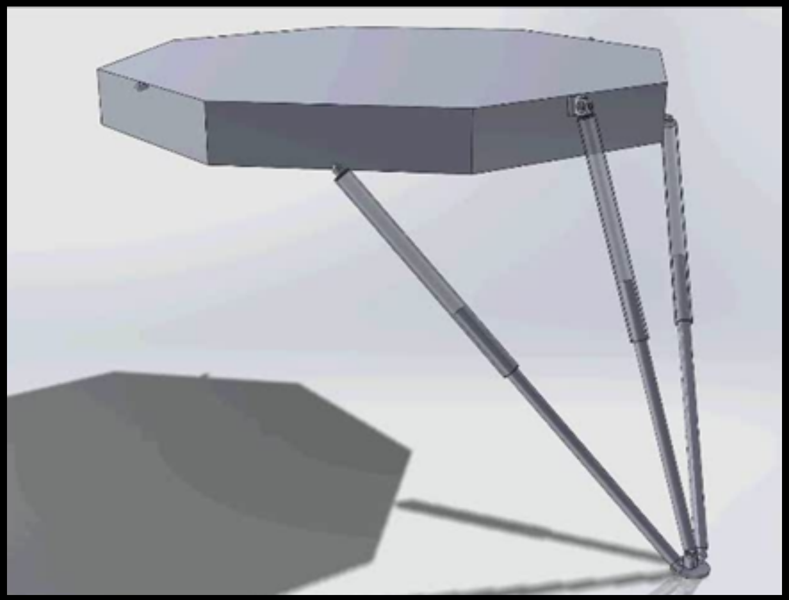
CANNOT SOLVE ANALYTICALLY

Simulation

SolidWorks Motion Studies



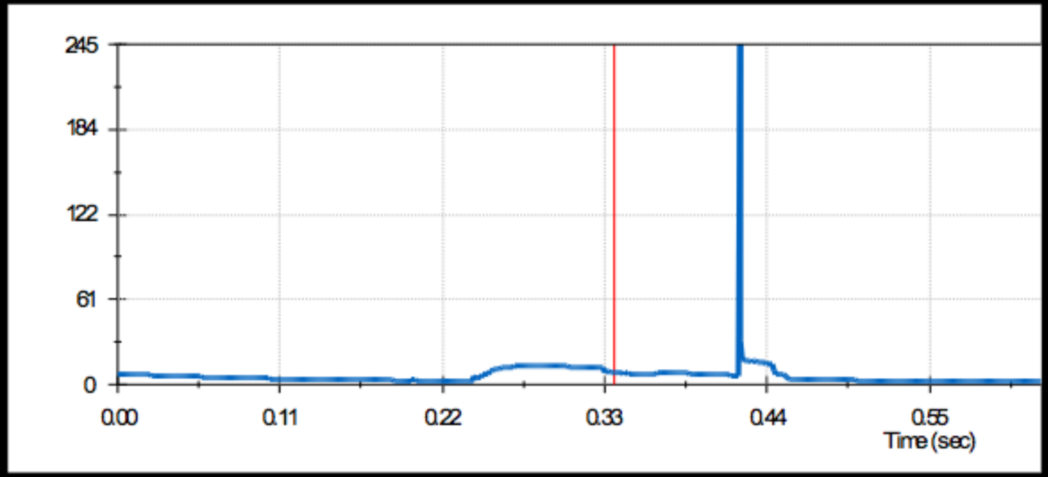
Single-leg initial impact



Vertical landing

Independent variables:

- Damping constants
- Spring constants
- Stroke lengths



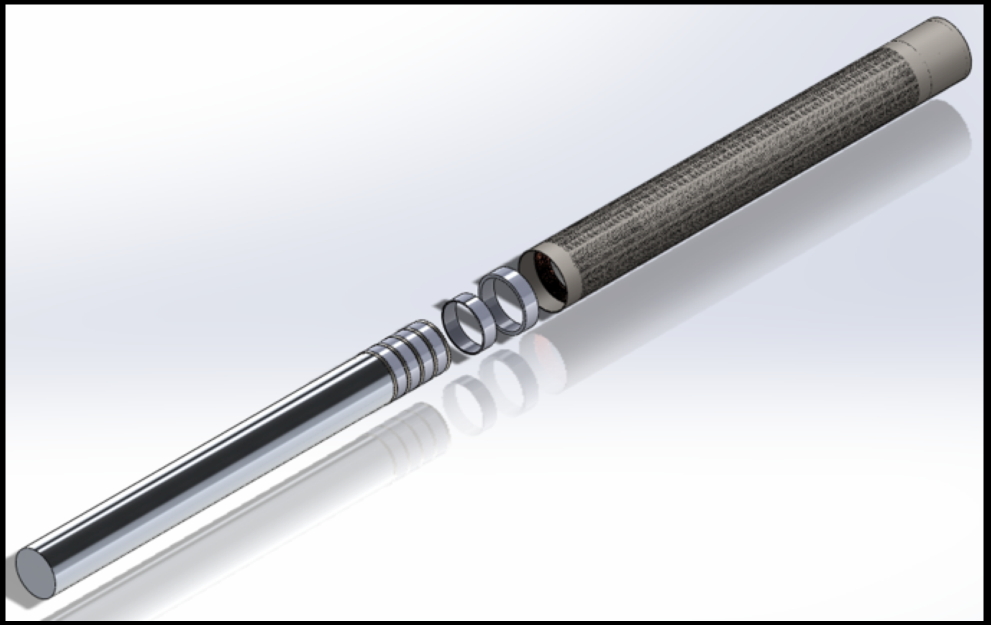
Deceleration vs. time graph of single-leg initial impact

Damping constant (all struts)	**1000 N s/m**
Spring stiffness (all struts)	**800 N/m**
Stroke of primary strut	**0.667 m**
Stroke of secondary struts	**0.600 m**

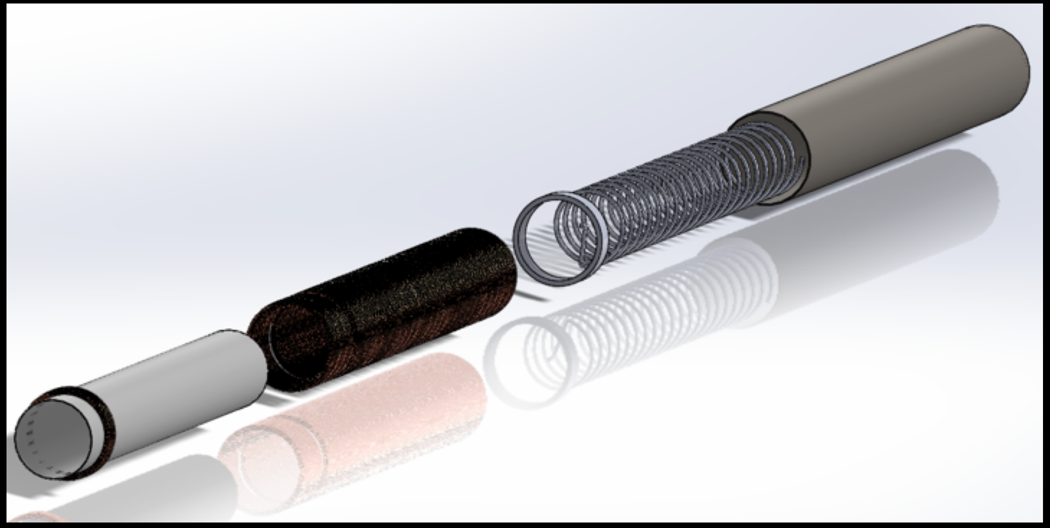
Final values

Final Design

Final Landing Gear Design



Exploded Strut



Exploded Stator

Thank You

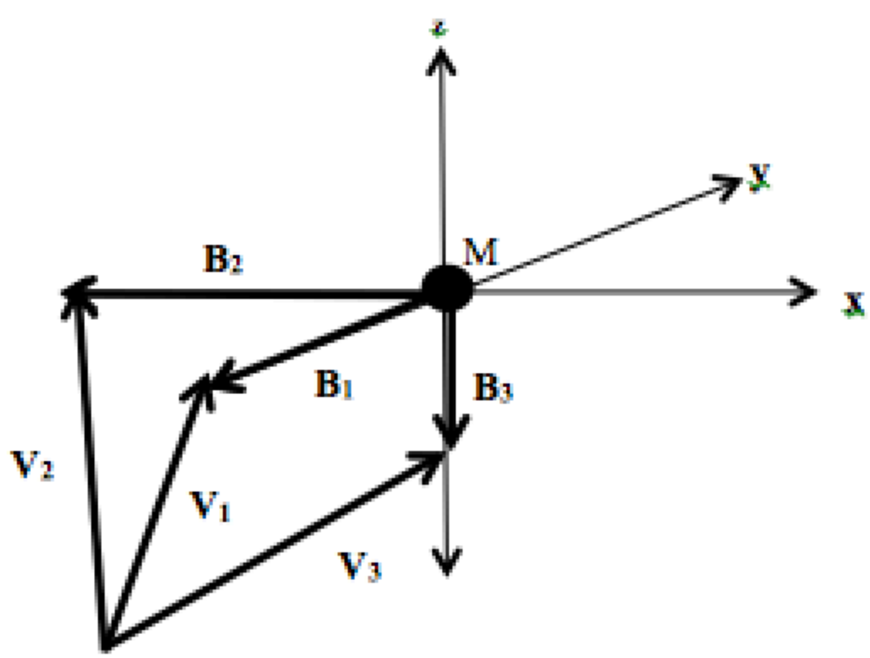
Questions?

Appendix

Equation of Motion:

$$m\ddot{z} + mg - k_p\left(\frac{l_{p0}}{l_p} - 1\right)(z+b) - 2k_s\left(\frac{l_{s0}}{l_s} - 1\right)(z+d)$$

$$= -\dot{z}\left[c_p\frac{(z+b)^2}{x_1^2 + y_1^2 + (z+b)^2} + 2c_s\frac{(z+d)^2}{x_1^2 + y_2^2 + (z+d)^2}\right]$$



Appendix

Budget Calculations:

Found volume of each material in design and multiplied it by its density to find its mass

$$= \left(m \cdot \frac{Price}{kg}\right)_{Cu} + \left(m \cdot \frac{Price}{kg}\right)_{Al} + \left(m \cdot \frac{Price}{kg}\right)_{Stl} + \left(N_{NdFeB} \cdot \frac{Price}{N_{NdFeB}}\right)$$

$$+ .15(Cost_{Cu} + Cost_{Al} + Cost_{Stl})$$

$$= \left(133.76\, kg \cdot 6.77 \frac{\$}{kg}\right)_{Cu} + \left(25.48\, kg \cdot 1.76 \frac{\$}{kg}\right)_{Al} + \left(95.8\, kg \cdot 1.10 \frac{\$}{kg}\right)_{Stl}$$

$$+ \left(48\, magnets \cdot 228 \frac{\$}{N_{NdFeB}}\right) + .15(Cost_{Cu} + Cost_{Al} + Cost_{Stl} + Cost_{NdFeB})$$

$$\approx \$13{,}800$$